Indian Journal of Science and Technology Vol. 3 No. 12 (Dec 2010) ISSN: 0974- 6846

Experimental investigations on CI engine in HCCI and conventional diesel mode

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Abstract

An experimental investigation was carried out in diesel engine operated in both homogeneous charge compression ignition (HCCI) and conventional modes. The engine used in this investigation is single cylinder, 4 stroke, water cooled, constant speed, variable compression ratio diesel engine with a displacement of 553 cc. In conventional diesel mode, the fuel was injected 27^0 bTDC with a nozzle included angle 140^0 and the compression ratio 16.5. In HCCI mode, the fuel was injected 80^0 bTDC during compression stroke by using modified camshaft, with a nozzle 60^0 included angle. In HCCI mode, to control the phasing and rate of combustion, the effective compression ratio was reduced to 14.5. From the experimental results it is inferred that, HCCI mode of operation results in reduced smoke and NOx emissions significantly with a little increase of HC and CO emissions.

Keywords: Engine, HCCI, injection timing, injection pressure, emissions

Introduction

The increasingly strict restrictions being placed on diesel engine emissions have increased the interest in alternative combustion concepts. HCCI is one of these concepts and has proven to be capable of reducing both NOx and smoke emissions significantly. A major advantage of HCCI is that, it shows potential to meet stringent future emission regulations without the need for NOx and soot after treatment systems. In HCCI, a homogeneous air-fuel mixture is compressed and self-ignited. Due to the fact that the mixture is homogeneous and lean, there are no soot-producing fuel-rich zones. The degree to which NOx and soot production is eliminated depends partly on the actual homogeneity of the mixture. The HCCI engine is an alternative to the conventional gasoline or diesel engine. In fact, HCCI could be regarded as a type of operating mode rather than a type of engine. The main objective of HCCI combustion is to reduce NOx and smoke emissions. In gasoline engines, a near stoichiometric mixture is burned with a relatively high temperature flame front where NOx is formed. On the other hand, the inhomogeneity of diesel combustion results in high smoke from fuel-rich regions and high NOx from high temperature regions. The HCCI engine is usually operated at part load under which the lean homogeneous mixture auto-ignites at multiple locations in the cylinder. The mixture is lean so that less NOx is formed. Meanwhile, the mixture is homogeneous so that less smoke formation is observed. The lean homogeneous mixture burns at relatively low temperature which results in low heat loss and hence high fuel efficiency can be achieved. In addition, no throttling (as in gasoline engine) or high-pressure fuel injection system (as in diesel engines) is needed, which also results in better efficiency and low cost. Since the start of combustion is determined by the in-cylinder conditions, there is no direct control of the combustion phasing. The in-cylinder conditions can be altered by varying the compression ratio, intake air temperature and EGR rate.

However, there are still challenges associated with the successful operation of HCCI engines. One of the difficulties is to control the combustion phasing mainly the assurance of auto-ignition appropriate timings over a wide range of operating conditions. Another obstacle of HCCI engine operations is the relatively high emissions of unburned hydrocarbon (HC) and carbon monoxide (CO) due to the incomplete combustion of low temperature lean burn. The power output of the HCCI engine is also limited since the combustion can become unstable and knock-like cylinder pressure oscillations occur as the mixture approaches stoichiometric. Other challenges include the proper preparation of the mixture, utilization of exhaust gas recirculation (EGR) and optimization under transient operations (Rudolf & Charles, 1999).

Various research groups have presented work in which they describe the use of diesel fuel for HCCI operation. The main objective of the HCCI combustion is to reduce smoke and NOx emissions while maintaining high fuel efficiency at part load conditions (Thring, 1989). Magnus & John (2004) have investigated, where diesel fuel is injected early in the compression stroke, is often referred to as PREDIC (Premixed lean diesel combustion) and concluded that early injection 45° bTDC reduces NOx. Although the low ignition resistance of diesel fuel makes the combustion phasing and rate more difficult to control, it has the advantage that part load HCCI operation can be combined with conventional diesel operation at higher loads (Hasegawa & Hiromichi, 2003; Arjan *et al.,* 2005). The fuel can be injected in the intake system or directly into the cylinder during the compression stroke (Hardy & Reitz, 2006). A combination of early injection and injection around TDC is reported to reduce NOx and soot levels (Nakagome *et al.,* 1997; Kim & Lee, 2005). The combustion phasing and rate of heat

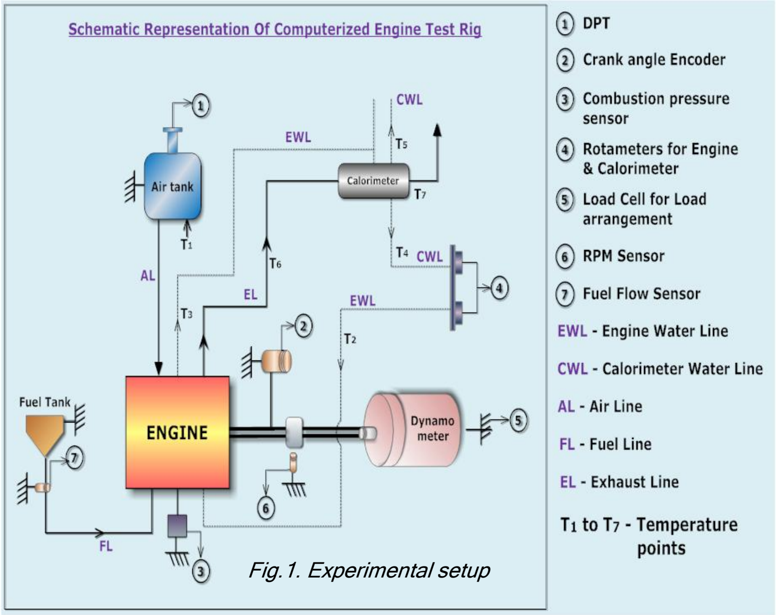


Fig.1. Experimental setup

Fig. 2. Variation of brake thermal efficiency with load.

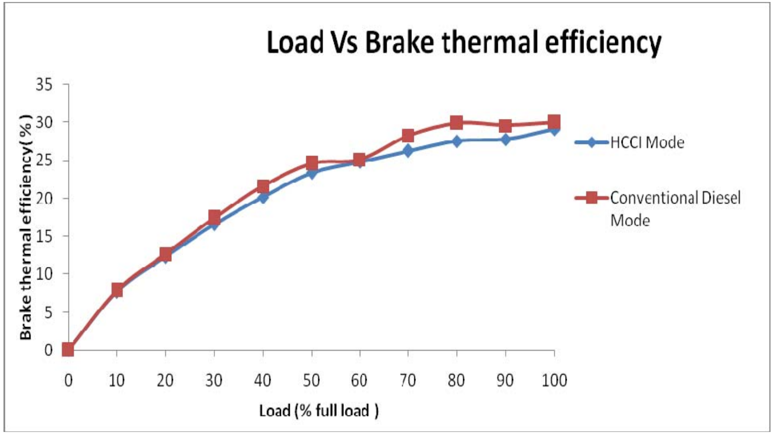


Fig. 6. Variation of heat release rate with crank angle.

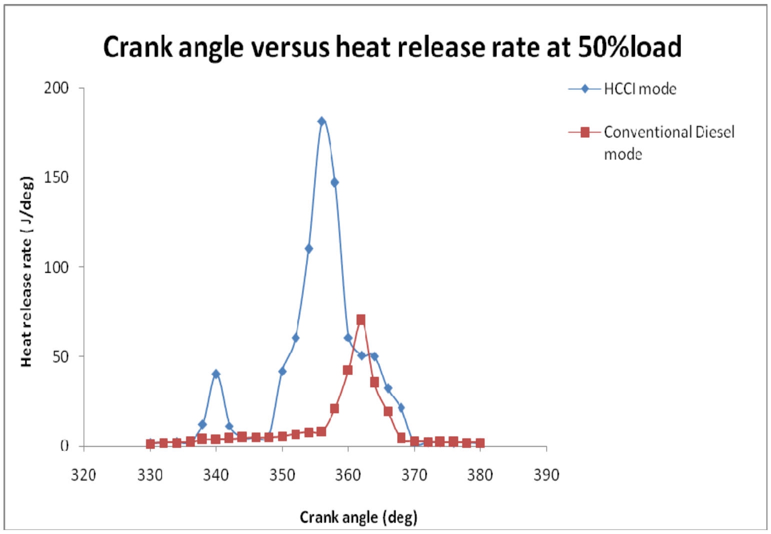


Fig. 3. Variation of unburned hydrocarbons with load.

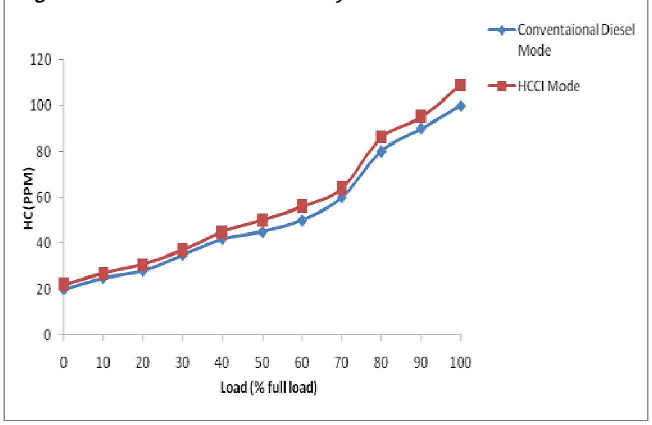
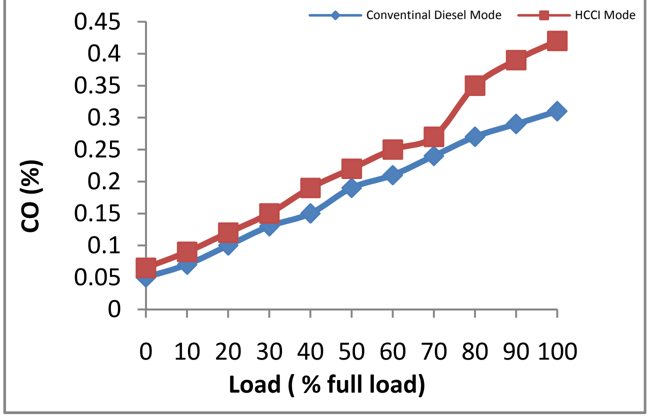


Fig.4. Variation of CO with load.



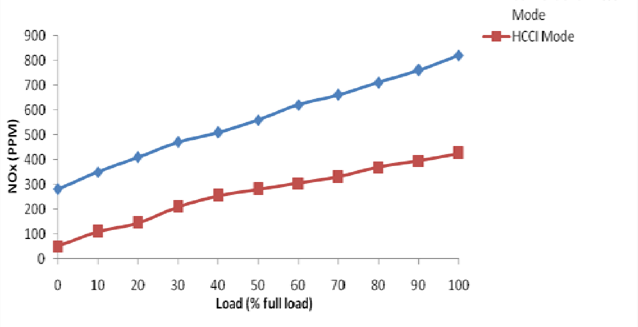


Fig. 5. Variation of NOx with load.

Table 1. Engine specifications.

Manufacturer	Kirloskar engines Ltd., Pune, India
Engine Type	Four stroke, single cylinder, constant speed, compression ignition engine
Rated power	3.7 kW at 1500 rpm
Bore	80 mm
Stroke	110 mm
Swept volume	553 cc
Compression Ratio	12.5-21.5
Mode of injection	Direct injection
Cooling system	Water
Dynamometer	Eddy current dynamometer

release can be controlled by changing the compression ratio (Timoty *et al.,* 2005), EGR rate (Kim & Lee, 2005), injection strategy (Ralf *et al.,* 2004) or combination of these measures.

Table 2. Properties of diesel fuel.

Cetane number	53
Density at 30^0C	836 kg/m^3
Viscosity at 40^0C	2.68 mm^2/s
Calorific value	42500 KJ/Kg

In HCCI mode, a lower compression ratio is required in order to prevent too early ignition of the diesel fuel. However, the required compression ratio for HCCI is typically too low for satisfactory performance in conventional diesel mode, so the compression ratio must be varied if both modes are to be combined. Depending on the injection strategy, different nozzle geometries may be needed for HCCI. When the fuel is injected early during the compression stroke, spray interaction with the cylinder liner may occur, in which case a nozzle with narrow included angle would be needed.

Materials and methods

Experimental setup

The experimental setup used in this investigation is shown in Fig. 1. It consists of a single cylinder, 4 stroke, constant speed, water cooled, variable compression ratio, direct injection compression ignition engine with hemispherical open combustion chamber. The fuel injection system of the engine comprised of a plunger type pump with an injector having 3 spray holes, each 0.28 mm diameter. The injector needle lift pressure and fuel injection timing of the engine are 210 bar and 27^0 bTDC respectively. The specifications of the engine are shown in Table 1. A single cylinder 4 stroke water cooled diesel engine was coupled to an eddy current dynamometer with a load cell. The in-cylinder pressure was measured by piezoelectric pressure transducer (Kistler) fitted on the engine cylinder head. A crank angle encoder was used to sense the crank position. Exhaust gas analysis was performed using five gas exhaust analyzer (Netel make). A Hartridge smoke meter was attached to exhaust pipe to measure smoke levels.

Experiments & procedures

The engine was operated in conventional diesel mode and HCCI mode with diesel as fuel. The properties of the diesel fuel are shown in Table 2. In both modes, experiments were conducted at variable load at rated speed 1500 rpm. In conventional diesel mode, the engine was operated with fuel injection timing 27^0 bTDC and the compression ratio used was 16.5. In order to operate the engine in HCCI mode, the fuel was injected 80^0 bTDC and the compression ratio used was 14.5. For HCCI operation, intake camshaft with increased opening duration was used to inject fuel at 80^0 bTDC. The fuel injector was fitted with a special ten-hole nozzle with an included angle of 60^0. This narrow angle was chosen because experiments showed that in HCCI mode, the use of a conventional 140^0 nozzle caused spray interaction with the cylinder liner, and therefore increased smoke, HC and CO emissions. At each load air flow rate, fuel flow rate, exhaust gas temperature, HC, CO, NOx and smoke emissions were recorded.

Results and discussion

The variation of brake thermal efficiency with load is shown in Fig. 2. In conventional diesel mode, the brake thermal efficiency is slightly more than the HCCI mode of operation due to lower compression ratio used in later mode of operation. At full load condition, the brake thermal efficiency of conventional engine is 30.02% where as it is 29.12% with HCCI. Fig. 3 and Fig. 4 show the trends of unburned hydrocarbons (HC) and carbon monoxide (CO) emissions with load. The HC and CO emissions were more in case of HCCI mode due to incomplete combustion of low temperature lean burn operation.

Fig. 5 shows variation of NOx with load in both modes of operation using diesel as fuel. In conventional mode of operation, the inhomogeneity of diesel combustion results in high NOx from high temperature regions. The HCCI engine is usually operated at lean homogeneous mixture auto-ignites at multiple locations in the cylinder. The

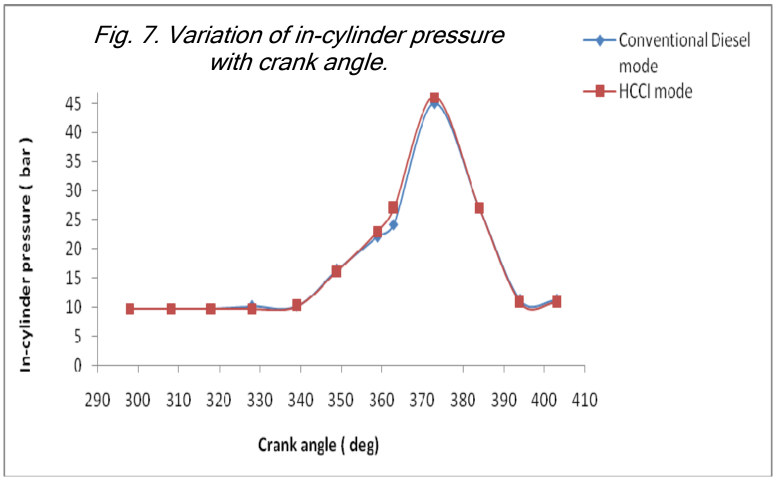


Fig. 7. Variation of in-cylinder pressure with crank angle.

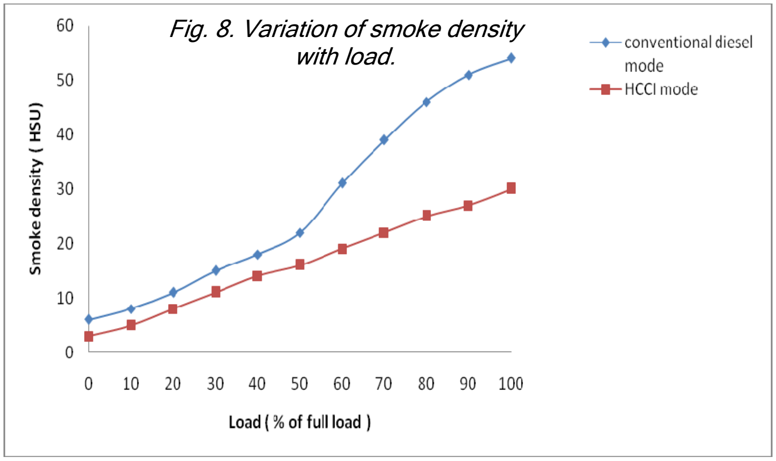


Fig. 8. Variation of smoke density with load.

mixture is lean so that less NOx is formed. At 70% of full load, it is observed that NOx emissions for conventional operation is 660 ppm where as it is 385 ppm with HCCI operation. In HCCI operation, a steep rise of NOx is observed above 70% of load due to high temperature available inside the engine cylinder.

Fig. 6 shows variation of heat release rate with crank angle at 50% of full load. In HCCI operation, the peak heat release rate occurs at a crank angle 356° whereas it is 362° with conventional engine. The peak heat release rate for HCCI operation is 181.32 J/deg and it is 70.23 J/deg for conventional operation. The peak heat release rate is more in case of HCCI mode of operation due to the homogeneous mixture is formed before combustion. The variation of in-cylinder pressure with crank angle at 50% of full load is shown in Fig. 7. A slight variation of in-cylinder pressure was observed when both the cases are compared. The peak pressure in HCCI operation is 46.1 bar where as it is 45 bar with conventional operation. The variation of smoke density with load is shown in Fig. 8. As load increases, smoke density increases for both cases of operation. But after 50% load, steep rise of smoke density was observed. At full load, the smoke density of conventional engine is 54 HSU where as it is 30 with HCCI.

Conclusions

The performance, emission and combustion characteristics of DI diesel engine were analyzed and compared in conventional diesel mode and HCCI mode. There was a reduction in brake thermal efficiency for HCCI mode by 2.99% compared to conventional diesel mode at full load. It is observed that the HC and CO emissions were higher in HCCI mode than conventional diesel mode. There was a reduction in NOx emission for HCCI mode of operation by 41.66% compared to conventional diesel mode at 70% of full load. There was an increase in peak heat release rate for HCCI mode when compared to conventional diesel mode. Smoke density was reduced by 44.4% in case of HCCI operation when compared with conventional diesel mode. The conventional diesel engine is converted into HCCI mode and it was observed from the experiments that NOx and smoke emissions were very less when compared with conventional diesel mode to meet the future stringent emission regulations.

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